Hard Rescattering in QCD and High Energy Two-Body Photodisintegration of the Deuteron

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Photon absorption by a quark in one nucleon followed by its high momentum transfer interaction with a quark in the other may produce two nucleons with high relative momentum. We sum the relevant quark rescattering diagrams, to show that the scattering amplitude depends on a convolution between the large angle pn scattering amplitude, the hard photon-quark interaction vertex and the low-momentum deuteron wave function. The computed cross sections are in reasonable agreement with the data.

1. Introduction

The experiments on high energy two-body photodisintegration of the deuteron[1,2] set a new stage in high energy ($E_\gamma \geq 1$ GeV) nuclear physics. The conventional mesonic picture of nuclear interactions failed to describe the qualitative features of these measurements. Thus these experiments are unique in testing the implications of quantum chromodynamics QCD in nuclear reactions [3,4].

One of the first predictions for $\gamma d \to pn$ reactions within QCD was that according to the quark counting rule: $d\sigma/dt \sim s^{-11}$. This prediction was based on the hypothesis that the Fock state with the minimal number of partonic constituents will dominate in two-body large angle hard collisions[5]. Although successful in describing energy dependences of number of hard processes, this hypothesis does not allow to make calculation of the absolute values of the cross sections. Especially for reactions involving baryons, the calculations within perturbative QCD underestimate the measured cross sections by orders of magnitude see e.g.[6]. This may be the indication that in the accessible range of energies bulk of the interaction is in the domain of the nonperturbative QCD[6,7]. On the other hand even if we fully realize the role of the nonperturbative interactions the theoretical methods of calculations are very restricted.

Here we investigate the effects in which the absorption of the photon by a quark of one nucleon, followed by a high-momentum transfer (hard) rescattering with a quark from the second nucleon, produces the final two nucleon state of large relative momenta. We demonstrate that the structure of hard interaction for this rescattering mechanism is similar to that of hard NN scattering. Therefore the sum of the multitude of diagrams with incalculable nonperturbative part of the interaction is expressed through the experimentally measured amplitude of hard np scattering.

Another important feature of discussed mechanism is that its dominant contribution comes from the low relative momentum (< 300 MeV/c) of two nucleons. Therefore for the deuteron wave function one can use conventional wave functions calculated using the realistic nucleon-nucleon potentials.

2. Kinematic Requirements

The use of the partonic picture requires that the masses of the intermediate hadronic state produced by the γN interaction be larger than some minimum mass characterizing the threshold to reach the continuum. This is known from deep inelastic scattering[8] to be $W \approx 2.2\ GeV$. Here the mass of the intermediate (between the photon absorption and quark rescattering) virtual state is $m_{int} \sim \sqrt{2E_\gamma m_N}$. From the condition $m_{int} \geq W$ one obtains $E_\gamma \geq 2.4\ GeV$. Next, the struck quark (Fig. 1) should be energetic enough to reach the quark of the other nucleon without radiating soft (bremsstrahlung) gluons. From the regeneration length of the soft gluonic field one obtains the condition: $E_\gamma \geq r_N/R^2_{regen} \sim 2\ GeV$. Finally, to ensure that the quark rescattering is hard enough, one requires that: $-t, -u \geq 2\ GeV^2$.

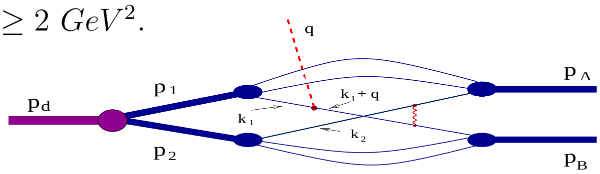

Figure.1 Quark Rescattering diagram.

3. Derivation of Differential Cross Section

Our derivation proceeds by evaluating Feynman diagrams such as Fig. 1. The quark interchange mechanism, in which quarks are exchanged between nucleons via the exchange of a gluon, is used. All other quark-interactions are included in the partonic wave function of the nucleon, ψ_N. We use a simplified notation in which only the momenta of the interacting quarks require labeling. The scattering amplitude T for photo-disintegration of a deuteron (of four-momentum p_d and mass M_d) into two nucleons of momentum p_A and p_B is given by:

$$T = -\sum_{e_q}\int\Bigg(\frac{\psi^\dagger_N(x'_2, p_{B\perp}, k_{2\perp})}{x'_2}\bar{u}(p_B - p_2 + k_2)\left[-igT^F_c\gamma^\nu\right]\frac{u(k_1+q)\bar{u}(k_1+q)}{(k_1+q)^2 - m_q^2 + i\epsilon}$$
$$\left[-ie_q\epsilon^\perp\cdot\gamma^\perp\right]u(k_1)\frac{\psi_N(x_1, p_{1\perp}, k_{1\perp})}{x_1}\Bigg)\Bigg\{\frac{\psi^\dagger_N(x'_1, p_{A\perp}, k_{1\perp})}{x'_1}\bar{u}(p_A - p_1 + k_1)\left[-igT^F_c\gamma_\mu\right]$$
$$u(k_2)\frac{\psi_N(x_2, p_{2\perp}, k_{2\perp})}{x_2}\Bigg\}G^{\mu\nu}\frac{\Psi_d(\alpha, p_\perp)}{1-\alpha}\frac{dx_1}{1-x_1}\frac{d^2k_{1\perp}}{2(2\pi)^3}\frac{dx_2}{1-x_2}\frac{d^2k_{2\perp}}{2(2\pi)^3}\frac{d\alpha}{\alpha}\frac{d^2p_\perp}{2(2\pi)^3}, \qquad (1)$$

where p_1 and p_2 are the momenta of the nucleons in the deuteron, with $\alpha \equiv \frac{p_{1+}}{p_{d+}}$, $p_2 = p_d - p_1$ and $p_{1\perp} = -p_{2\perp} \equiv p_\perp$. Each nucleon consists of one active quark of momenta k_1 and k_2: $x_i \equiv \frac{k_{i+}}{p_{i+}} = \frac{k_{i+}}{\alpha p_{d+}}$ $(i = 1, 2)$. $G^{\mu\nu}$ describes the gluon exchange between interchanged quarks. We use the reference frame where $p_d = (p_{d0}, p_{dz}, p_\perp) \equiv (\frac{\sqrt{s'}}{2} + \frac{M_d^2}{2\sqrt{s'}}, \frac{\sqrt{s'}}{2} - \frac{M_d^2}{2\sqrt{s'}}, 0)$, with $s = (q + p_d)^2$, $s' \equiv s - M_D^2$, and the photon four-momentum is $q = (\frac{\sqrt{s'}}{2}, -\frac{\sqrt{s'}}{2}, 0)$.

To proceed we analyze the denominator of the knocked-out quark propagator, when recoil quark-gluon system with mass m_R is on mass shell. We are concerned with momenta such that $p_\perp^2 \ll m_N^2 \ll s'$ and $\alpha \sim \frac{1}{2}$ so we neglect terms of order $p_\perp^2, m_N^2/s' \ll 1$ to obtain:

$$(k_1+q)^2 - m_q^2 + i\epsilon \approx x_1 s'(\alpha - \alpha_c + i\epsilon), \text{ with } \alpha_c \equiv \frac{x_1 m_R^2 + k_{1\perp}^2}{(1-x_1)x_1\tilde{s}}, \tag{2}$$

where $\tilde{s} \equiv s'(1+\frac{M_d^2}{s'})$. Next we calculate the photon-quark hard scattering vertex and integrate over the α using only the pole contribution in Eq.(2). Note that the dominant contribution arises from the soft component of the deuteron when $\alpha_c = \frac{1}{2}$, which according to eq.(2) requires $k_{1\perp}^2 \approx \frac{(1-x_1)x_1\tilde{s}}{2}$.

Summing over the struck quark contributions from photon scattering off neutron and proton one can express the scattering amplitudes through the pn hard scattering amplitude within QIM-$A_{pn}^{QIM}(s,l^2)$ as follows:

$$T \approx \frac{ie(\epsilon^+ + \epsilon^-)(e_u+e_d)}{2\sqrt{s'}} \int f(\frac{l^2}{s}) A_{pn}^{QIM}(s,l^2)\Psi_d(\frac{1}{2},p_\perp)\frac{d^2p_\perp}{(2\pi)^2}. \tag{3}$$

where $\epsilon^\pm = \frac{1}{2}(\epsilon_x \pm i\epsilon_y)$ and e_u and e_d are the electric charges of u and d quarks. The factor $f(l^2/s)$ accounts for the difference between the hard propagators in our process and those occurring in wide angle pn scattering. Within the Feynman mechanism[8], the interacting quark carries the whole momentum of the nucleon ($x_1 \to 1$), thus $f(l^2/s) = 1$. Within the minimal Fock state approximation, $f(l^2/s)$ is the scaling function of the θ_{cm} only with $f(\theta_{cm} = 90^0) \approx 1$[9].

We compute the differential cross section averaging $|T|^2$ over the spins of initial photon and deuteron and summing over the spins of the final nucleons. Then we use the observation that the quark interchange topologies are the dominant for fixed $\theta_{cm} = 90^0$ high momentum transfer (non strange) baryon-baryon scattering. Thus in the region of $\theta_{cm} \approx 90^0$ we replace A_{pn}^{QIN} by the experimental data - A_{pn}^{Exp} and obtain[9]:

$$\frac{d\sigma^{\gamma d\to pn}}{dt} = \frac{4\alpha}{9}\pi^4 \cdot \frac{1}{s'}C(\frac{t_N}{s})\frac{d\sigma^{pn\to pn}(s,t_N)}{dt} \times \left| \int \Psi_d^{NR}(p_z=0,p_\perp)\sqrt{m_N}\frac{d^2p_\perp}{(2\pi)^2}\right|^2, \tag{4}$$

where $t_N = (p_B - p_d/2)^2$. Eq. (4) shows that the $\frac{d\sigma^{\gamma d\to pn}}{dt}$ depends on the soft component of the deuteron wave function, the measured high momentum transfer $pn \to pn$ cross section and the scaling factor $C(\frac{t_N}{s}) \approx f^2(t_N/s) \approx 1$ at $\theta_{cm} \sim 90^0$ (and slowly varying as a function of θ_{cm}) and the additional factor coming from the $\gamma - q$ interaction.

4. Comparison with the Data

In the numerical calculations we take $C(\frac{t_N}{s}) = 1$ and use Ψ_d^{NR} calculated with Paris potential. Our calculation produces band because of the accuracy of experimental data on $\frac{d\sigma^{pn\to pn}}{dt}$ and our interpolation to the required (s,t) bins. Figure 2 shows that calculations are in agreement with the measured differential cross sections. Moreover the agreement improves for larger θ_{cm} which confirms our expectation that $C(t_N/s) \approx 1$ at $\theta_{cm} = 90^0$. The deviations from the calculation based on the approximation $C(\theta_{cm}) = 1$ seem to be consistent with C being a function of θ_{cm} only. In particular the whole set of available data can be described (Fig.3) by taking $C(t_N/s) = \frac{-2t_N/s'}{1+2t_N/s'} \approx \frac{-t/s'}{1+t/s'}$ including even the data at $\theta_{cm} = 36^0$ where $(-t \lesssim 2\ GeV^2)$ and the hard interaction mechanism can not be applied. This may indicate that connection between NN and $\gamma d \to pn$ dynamics extends to a transitional region of t.

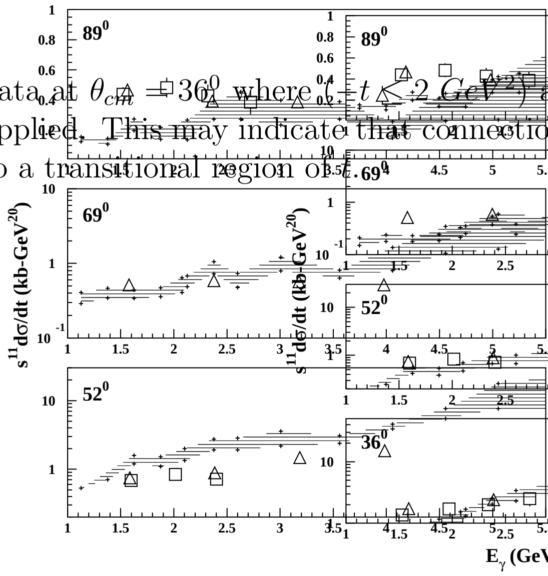

Figure 2. The $d\sigma/dts^{11}$ as a function of E_γ. Data are from [1] (triangles)and [3] (squares).

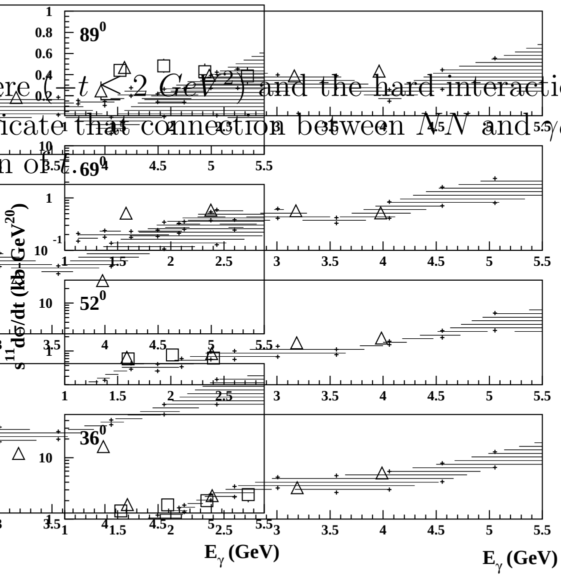

Figure.3 The same as in Figure.2, with $C(t_N/s) = \frac{-2t_N/s'}{1+2t_N/s'}$.

5. Summary and Outlook

The agreement with the data verifies our underlying hypothesis that the size of the photoproduction reaction is determined by the physics of high-momentum transfer contained in the hard scattering NN amplitude. The short-distance aspects of the deuteron wave function are not important. This hypothesis, if confirmed by additional studies, may suggest the existence of new type of quark-hadron "duality", where the sum of the "infinite" number of quark interactions could be replaced by the hard amplitude of NN interaction.

More data, especially with a two proton final state (i.e. $\gamma +^3 He \to pp$ (high p_t) + n ($p_t \approx 0$)), and a more detailed angular distribution would definitely allow to verify this hypothesis. The polarization measurement also will be crucial especially at the same s where anomalies observed in hard pp scattering. Another important extension would be similar experiments using virtual photons.

The present calculations could be extended also to the reactions with a different composition of final high p_t hadrons, which could allow the study the mechanism of the rescattering different from the quark interchange.

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